Coiled Tubing: State of the Industry and Role for NETL

Topical Report

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INTRODUCTION

The use of coiled tubing (CT) to conduct well intervention services is well established. With improving technology, the use of CT has continued to grow at an average rate of ten percent per year, even as other services decline. The National Energy Technology Laboratory (NETL) has historically and currently sponsors and directs a number of CT related research projects as part of the U.S. Department of Energy (DOE) goal to develop technologies to recover a higher percentage of domestic oil deposits and slow the decline of U.S. oil production. A recent study was conducted to help formulate a road map for future co-funded research in coiled tubing, coiled tubing drilling (CTD), slimhole/microhole and related technologies. The thrust of the first phase was to look at this relatively new (CTD) industry: identify the level of activity, the dominant service providers, applications and geographical distribution of activity. Second, to examine, in some detail the use of coiled tubing for grass roots drilling – the advantages, disadvantages, limitations, costs and why it has flourished in Alberta Province and not elsewhere, particularly the lower 48 states. Finally, the results of a technology assessment was reported: identifying the cutting edge applications that are out in the field and what research is underway with Joint Industry Partners, universities and technology companies, some DOE co-funded, much of it not. Information was gathered through available public sources and through private discussions with a spectrum of industry experts.

The second phase of the study focused on DOE funded research for coiled tubing generally, and coiled tubing drilling in particular. The related interest areas of slimhole/microhole drilling, high speed drilling and monitoring gas-flooded oil reservoirs with vertical seismic profiling were also examined. The research in these areas co-funded by DOE in the mid-1990s was general in nature. This is in contrast with the focused research in the above topics begun in the last two years. An assessment of industry acceptance and potential market was made for coiled tubing well intervention; coiled tubing conveyed drilling of slimholes/microholes for shallow production, exploration logging, lateral extension, and reservoir monitoring. In this phase as well, information was gathered from both public sources and private discussions with the principal investigators of DOE co-funded projects and other industry experts.

Applications: Well intervention and drilling

Coiled tubing is just as the name indicates. It is a continuous length of ductile steel or composite tubing stored and transported in a coil on a large reel. Tubing sizes range from 1 inch to 4 ½ inches. The bigger the diameter, the deeper it can be used, but the more it weighs. The reel diameter must be at least 48 times the diameter of the tubing, to avoid excessive stress. It can be uncoiled in the well and returned back to the reel up to 50 or more times before metal fatigue forces retirement.

The historic roots of the Coiled Tubing industry has been in the jetting of well bores to clean up or initiate flow and that is still the “bread and butter” of the service industry. But in the last 15 years with stronger tubing, better tools and new technology, coiled tubing can be used in any application rotary rigs can do within certain limitations on depth (or length), temperature and cost. And in many cases can do it faster, easier and cheaper. There are a number of companies making tools and bottomhole assemblies (BHAs) for coiled tubing and slimhole applications. Coiled Tubing can be used in most well intervention applications performed by jointed pipe workover rigs, including

Well Cleaning and other Pumping Operations

- Removal of sand, wax and other plugs
- High pressure jet washing
- Pulsating jet washing
- Scale removal
- Unloading water with Nitrogen pumping
- Single and multi-zone acid treatments
- Single and multi-zone fracturing
- Cutting tubulars with fluid
- Cementing and plugging

Completion and other Mechanical Operations

- Straddles for zone isolation
- Retrievable bridge plug
- Retrievable packers
- Through tubing applications
- Fishing
- Perforating
- Logging
- Milling and mechanical cutting of tubulars
- Shifting sliding sleeves
- Flow management- velocity strings

A more complete description of these applications can be found on the website of the International Coiled Tubing Association (ICoTA) at www.icota.com and most service company sites.

In addition to well intervention, coiled tubing is used in several other applications: For example, coiled tubing deployed electric submersible pumps have been popular in Alaska, Qatar, West Africa, the North Sea and now are in limited Gulf of Mexico use. (9) Coiled tubing has also been used for remedial work in pipelines while still pressurized.

Coiled tubing drilling, which only makes up 15% of the revenues of the CT service industry, is growing faster than the intervention market. Most of the grass roots CT drilling is done in Canada for reasons that will be discussed later. Most of the Canadian CT drilling rigs can drill and set casing in the shallow Alberta gas wells. A few are true hybrids and can also rotate and spud in the surface casing and fish. Some of the other drilling applications include:

- · Slimhole casing exit technology
- · Restricted bore whipstock system
- · Underbalance drilling
- · High angle drilling
- · Precise steering and logging while drilling
- · Openhole completions and liner systems

Besides the standard operations listed above there are a number of leading edge and bleeding edge applications and research areas relating to Coiled Tubing Drilling cited in the literature:

Various new technologies designed to extend the horizontal reach of Coiled Tubing Drilling to 3,300 feet and beyond (1) (Leading Edge). They are

- · Larger diameter tubing and/or smaller liner
- · Effective lubricant additions to drilling mud can reduce friction by 45%
- · CT straightener on rig (extends reach, but reduces fatigue life)
- · Thruster or bumper subassembly provides a weight on bit proportional to differential pressure by acting like a hydraulic cylinder
- · Tractor or locomotive reacts against the borehole wall to provide pull (and possibly push) tubing and BHA
- · High pressure abrasive/water jet drilling provide zero weight on bit - currently used for window milling
- · Adding a rotator within the BHA (requires a second motor)
- · New materials – titanium and composite (expensive, low young's modulus respectively)
- · Counter rotating bit using a coring style bit with a typical bit immediate if from or behind it to allow the development of a zero force drilling system

Example Coiled Tubing Drilling future directions (bleeding edge) (2) include

- · Drill microholes for reservoir conformance (logging), monitoring (VSP), and productivity index (DOE solicitations)
- · Drilling and completion through sidetracks in tubing as small as 3 ½ inch
- · Continued development of expandable tubular technology for completions while drilling
- · CT and laser drilling and laser cutting applied with "liquid" casing technology developments
- · Continued development with concentric CT applications and systems to drill multilateral wells.
- · Smart electric coiled tubing drilling automatic adjustment to drilling conditions
- · Shorter tools to reduce length of BHA
- · Less expensive and longer lasting tools

Developments in Drilling from surface

- In 1976, Flextube drills 6 grass roots wells in Alberta to 2,000 feet with coil made from welded sections.
- Alberta, Mid-1990s through today – 42 second generation rigs with draw works and mast in pretty much continuous operation. Precision and Trailblazer dominate with 20 of the rigs and Ensign recently announced an order for 10 rigs. In total these rigs drill in excess of 2,500 wells/year, generally 3,000 feet deep or less. They are capable of drilling 2 wells/day with a workover rig moving in advance to set surface casing. Day rates average $14,000. They take 7 to 9 trailers to move, but rig up in 2 to 3 hours. They drill with mud overbalanced. 82% of wells in Alberta are 1,700 meters or shallower.
- Halliburton and Amoco 1995 - drilled first a 3 well, then a 5 well pilot in the San Juan basin 1,500 to 2,400 ft. depth. A workover rig was used to set casing, deemed economic.(4)
- Argentina 2001 - 30 well pilot, rig like Precision's used to drill 2500 ft gas wells, all wells online in 90 days, calculated at 90% equivalent rotary costs. Could have been faster with experience.(3)
- Technicoil 2001 - drilled 29 wells in San Juan CBM for Burlington Resources. (7)
- Alberta 2003 – third generation rigs in use by Technicoil – has rotary for setting surface pipe, gets up to 75 wells/coil. Drills up to 2 ½ wells/day. Rated at up to 9,800 ft. with 2 7/8 in. coil. It is beginning to be used to drill deeper oil wells.

Applications in through tubing, slim hole drilling side-tracking high angle wells in Alaska – in continuous use since 1995, 500 sidetracks from 1995 – 2004, 1,000 – 3,000 ft, hole sizes from 2 ¾ to 4 1/8 inch; cost at $1.2 million is half what rotary would be; drilled with dynamic overbalance mud (5)

Extensive use world wide of non-steered extension of an existing well in the underbalanced state, either vertical deepening or high angle

Horizontal or high angle underbalanced drilling with steering (MWD), logging (LWD), seismic (VSP) through installed electric lines for accurate bit placement (13)

Composite tubing with imbedded fibers for communications

The use of turbodrills for deeper, hotter and more complex wellbores (14)

Expanded use of Hybrid rigs with a hydraulic workover jacking system as an integral part of the unit allows for the performance of jointed pipe completions; a "new generation" rig has appeared recently with a top drive in addition to allow rotary drilling to set surface pipe and for fishing operations on the coil.

Coiled Tubing Drilling Advantages, Disadvantages, Limitations

Advantages:

- · Works like a snubber, can drill on existing wells without killing the well, or underbalanced – very helpful especially in horizontal – can control up to 10,000 psi surface pressure. (Safer in underbalanced situation)
- · Fast penetration – up to 200 ft/hour sustained (world record at 254m/hr), no trip or connection time
- · Faster trips
- · Unit mobility and faster rig up and rig down times associated with the new generation of CT rigs
- · Small footprint relative to standard rotary
- · Drills a gauge hole
- · Generally requires fewer people to operate than equivalent depth rotary because of overall system simplicity without connection requirements
- · With the new generation CTD rigs many applications can be accomplished with one piece of equipment.
- · More effective in precise positioning of tools in horizontal and vertical wells.

Disadvantages:

- · Limited capacity (size and weight of reel)
- · Tubing life – 30 – 50 wells for shallow (>3,000 ft) wells
- · Difficult to fish

Perceived Disadvantages:

- · Too expensive – uncompetitive for all hole types with rotary, especially truck mounted.
- · Too heavy to move over roads, under bridges.
- · Operators not trained for drilling operations.

Limitations:

- · Depth is limited by reel size and overall weight
- · CT hoisting capacity is limited by the injector that controls the penetration rate and insures the tubing is in tension, not compression
- · Casing capacity is limited by draw works and mast capacity (hybrid drilling unit)
- · Hole size is limited by pump requirements
- · Tubing life limits cycling
- · Rig dimensions limited by highway regulations
- · Limitation on how far it can be pushed (pulled) horizontally, even with tractors and equalizers.

Coiled Tubing Rigs and Companies

Coiled tubing rigs are categorized a number of ways: (1) by depth of service – shallow, medium and deep. 0 – 3,000 ft, 0 – 6,000 ft, and 0 – 15,000+ feet. (2) by land/offshore and transport – land, self propelled; land trailer transport on anywhere from 3 to 9 trailers; offshore platform mounted and ship mounted; and (3) purpose – shallow well cleanout (mostly found in Alberta), drilling rigs with mast and draw works (0 – 5,000 ft) that can run casing but cannot rotate (also found primarily in Alberta), hybrid rigs that can drill with jointed pipe or coil (0 – 5,000 ft), horizontal drilling rigs specializing in river and other barrier crossings, and the standard medium to deep CT rigs, used primarily for well intervention.

Regardless of size, purpose, or manufacturer, coiled tubing units all have the same five basic components: (1) power package to power the injector and mud pump, (2) control center, (3) injector, (4) the reel upon which the tubing is coiled, and (5) the blowout prevention stack. (See Figure 1 Below) The size, pressure rating, mounting of these five basic components are a function of pressure, working depth, application and transport method.

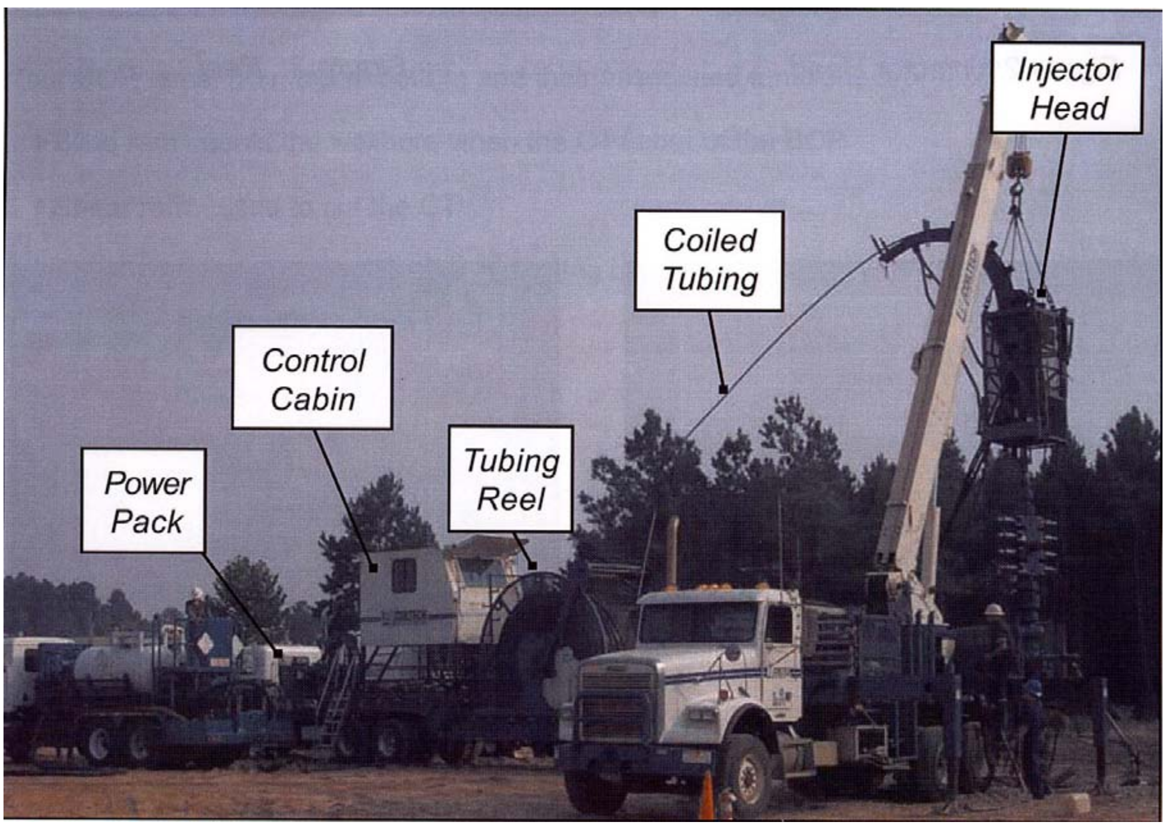

Figure 1. Trailer Mounted CT Unit and Crane – Courtesy International Coiled Tubing Association.

There are numerous companies that make one or more of the individual components above, but relatively few that manufacture a complete standard or custom built rig. The total worldwide market is in the 50 rigs/year range. See the Spears report (16) for a complete description of the companies (available for download at http://www.netl.doe.gov/scngo/Petroleum/index.html.)

Coiled Tubing

Most of the steel tubing in commercial applications comes from two manufacturers. Again, see Reference 16 for more complete discussion. The tubing is made at several manufacturing stations synchronized to form and weld steel strips into tubing on a continuous basis. It comes in a range of alloys with tensile strength from 70,000 to 120,000 lbs. and sizes from 1 inch to 4 ½ inches OD. Several companies make fiberglass coiled tubing, some with fibers for communication, but none are in commercial use at present.

Service Companies and Geographic Distribution

According to the 2005 ICoTA survey, there are approximately 1,182 Coiled Tubing rigs in service worldwide. In addition to the count, the survey lists the contractors and locations of the rigs. Internationally, there are 614 rigs. They are distributed in this manner - in the Middle East (128), in Europe/Africa (143), in South America (107), and in the Far East (236). As shown in the Spears report, the three largest service companies hold, collectively, a 70% market share.

Figure 2. Coiled Tubing Drilling Rig – Courtesy Tom Gipson, Coiled Tubing Services, Inc.

There is somewhat more diversity of companies in the U.S. market with 257 rigs, including 10 in Alaska in constant use for lateral extension drilling through the existing well bores in the North Slope. Canada's rig count is 311, but that is somewhat misleading. There are three classes of rigs in Western Canada. The first, with around 150 rigs is the mom and pop industry of very light, for purpose rigs that service the shallow (under 3,000 ft.) gas wells, basically providing jetting services. There are no dominant players in this market. The second category is also unique to Western Canada and that is the 42 built for purpose CT drilling rigs. These rigs will be discussed later and contrasted with rotary rigs. These rigs have a hoist and mast and can set pipe as well as drill. Several recent additions have rotary capability as well. (See Figure 2 above) The third class is the standard medium to deep conventional rig.

Economics of Canadian Coiled Tubing Drilling Versus Rotary

For almost a decade, in the face of a growing and successful coiled tubing drilling business in Alberta, the question has been asked as to why it has not been replicated elsewhere, particularly in the lower 48 United States. The answer is multifaceted, but would suggest that the obstacles certainly could be overcome, that it is more cultural and "chicken and egg" issues with infrastructure and large drilling programs than geology, economics or legal/environmental issues.

Culture – generally speaking, operators will use whatever technology is least expensive, assuming it is available when needed and does not increase risk of loss. Canadians appear to be somewhat more open-minded when it comes to adopting new technology. And when it came to drilling with CT did not have the bias of "It won't work here", "It's too expensive", or "The way I am doing it is just fine". In the early 90s the service providers were willing to take the risk of turnkey contracts to demonstrate the technology. With competitive rates, the business grew and with the advent of the for purpose drilling rigs that could drill the well and set the casing, working continuously the economics were tilted in favor of the CT rigs, versus the rotary. Some of the characteristics that favored the use of CT in Alberta include:

- Shallow (less than 3,000 ft) dry gas wells, 4 ½ inch casing, no tubing
- Thousands of wells drilled annually (allowing continuous drilling, not one and off)
- Relatively soft, predictable sediments (infrequent sticking)
- Rigs designed precisely to fit 3,000 ft. wells, experienced crews
- Small to no footprint, wells close together reducing transit time
- Fast move in and rig up time – 2 to 3 hours, fast penetration rates
- All weather operations

The cost per well for these type wells can be as low as $50,000, drilled and completed. Using the "cookie cutter" approach, all the inefficiencies have been squeezed out of the process. The CT drilling rigs are on day rate, typically $12,000/day plus approximately $2,000/well "coil charge" and mud. At two wells/day, that is $8,000/well. (2 ½ and 3 wells/day are not unheard of.) In addition, the operator pays for the surface pipe, and the cost of spudding it in, 3,000 feet of 4 ½ in casing, cement, wellhead, and minimal surface preparation.

In comparison, a rotary rig, also on day rate, works for $9,000/day in the summer and $12,000/day in the winter. But instead of two wells per day, it takes 1 – 2 days to drill the same well, resulting in drilling charges in the range of $15,000 to $25,000. The other charges to the operator are the same. It must be pointed out, however, that the CT day rate is applicable to a long term contract. Customers with large acreage positions will put the rigs under long term contract, up to a year, and direct how they are utilized.

There is no technical, legal, or environmental reason why for purpose rigs could not be redesigned or reconfigured to be U.S. Department of Transportation legal and used to drill shallow wells in the lower 48 states. While in general, transportation rules are less stringent in Canada, this does not preclude movement of lighter designed rigs, such as the rig operated by Coiled Tubing Services, Inc. in the western states (Figure 2). The rigs are all-weather and require little or no site preparation. There are no federal or provincial incentives provided in Canada, nor any legal barriers in the U.S. It would be most effective where there are blanket, shallow (2,000 – 4,000 ft) gas bearing sands, with hundreds or even thousand of locations requiring little, if any, geology. If the terrain is not mountainous, little site preparation would be required. Such areas can be found in Western Kansas, Northeast Colorado, Eastern Wyoming and West Texas.

Industry Experts

A number of CT industry experts, particularly in drilling, were contacted in conjunction with this study. Each aspect of the chain of CT drilling was covered: Research and Development, Manufacturing, Service companies, and producers in several shallow gas prone basins. A number of topics were discussed with each. They included (1) experience with CT and current activities, (2) involvement in any new research or applications, (3) any experience where CT worked particularly well, or not, (4) performance contrasted with rotary drilling, time, money, down time, (5) where the industry is headed – what's next?, and finally (6) recommendations for future DOE co-funded projects – microhole drilling, strength of materials, for purpose rigs and tools, high pressure high temperature applications, motors and bits, or other aspects.

Other than the producers, most of the subject matter experts (SMEs) interviewed belong to ICoTA, several as serve as directors. Many of the service companies and manufacturers discussed in the previous section on Coiled Tubing Rigs are represented in this group.

Generally speaking, the U.S. producers are not focused on CT drilling even those drilling shallow gas wells. They would entertain offers from drilling contractors for a fixed price contract below their $10/foot rotary costs, but the local CT service providers generally do not have the equipment, experience, or money to compete head on with the small water well drilling portable rotaries. The Canadian drilling contractors, having created the market for CT in the "perfect storm" drilling situation in Alberta have become the drillers of choice. Surprisingly, the three largest service companies with a 70% market share are, as a group, lukewarm on replicating the Canadian shallow drilling operations in the lower 48. In fact, they do not compete with the smaller CT drilling contractors in the Canadian market. They see the shallow gas drilling market as limited in scope and outside of their traditional product offering, preferring instead the global market in high pressure well intervention, underbalanced multilateral drilling from vertical wells, extra-long well remediation (e.g. 30,000 ft project at Sakhalin Island) and other high margin applications. Those that do have some interest are more or less sitting on the sidelines, waiting for the market to develop, rather than making the investment to push it along.

The manufacturers of rigs, coil and other related CT hardware are obviously in favor of displacing rotary rigs in the lower 48. And, as in Canada, the smaller local CT service companies, like Tom Gipson's Coiled Tubing solutions would welcome an expansion into slimhole and microhole CT drilling.

Current Industry Research

Virtually all basic and advanced applied research is being performed by universities or private technology companies sponsored by JIP groups sometimes with the participation of the U.S. Department of Energy. Some more applied research and field demonstration projects are co-funded by the DOE with industry or national lab partners. The large service companies participate in the JIPs, thereby limiting their own proprietary efforts to commercial products. Some of the groups and the ongoing research are: Tulsa University Coiled Tubing Mechanics Research Consortium has an ongoing program to predict failure and remediate defects in coiled tubing, extending the life. Maurer Engineering recently completed a project to provide software and evaluate new CT Technologies and are now working on a DOE sponsored research project in high pressure drilling. XL Technologies, a private British firm (www.xltl.com) has ongoing research in Electric CT Drilling with a built for purpose 3 1/8 inch direct to bit motor and integrated telemetry and drive.

Other sponsored university research includes work at Penn State utilizing microwaves to strengthen the steel while maintain its ductility, and University of Oklahoma investigating fluid friction losses in CT. These projects and others are described in more detail at the ICoTA web site (www.icota.com).

Future Research Direction Suggested by Experts

When the SMEs were asked where they would direct DOE research dollars to advance and commercialize technology, the answers were varied but clearly related to improving that aspect of the industry in which they were engaged. The producers generally were skeptical about the economics or the practicality of CT drilling and presumably would like a solid demonstration of the economics of CT drilling for shallow gas. A similar suggestion was received from those in the drilling business that had experience in Canada. All envisioned a push by DOE to create the highly mobile for purpose rigs and tools compete with the smaller rotary rigs. Maurer also suggested such equipment could convey their high pressure drilling technology.

Several of those in the drilling business would direct the research to the tubing itself, to make it cheaper by making it stronger, lighter, longer lasting. This was echoed by the TU consortium, while counseling not to lose sight of flaw tolerance in the quest for stronger and more ductile materials.

Several expressed doubts that the market for microhole drilling would support the creation of special rigs, tools and infrastructure. One pointed out that the cost threshold for microholes for chemical flood monitoring would be the cost to workover an existing wellbore, which should give research a measurable goal. One of the technology companies had two interesting suggestions: first, after spending tens of millions of dollars on offshore submerged CT drilling, work should be done to move the reel, but not the injector to a boat or platform, and second to install a "throw away" pressure and temperature device for use in CT stimulation that would basically stay with the tubing for as long as the tubing lasted.

Much of the DOE sponsored research in the 1990s and early 2000s was directed to field demonstration, to push technology previously practiced only by the majors down to the independents who were operating most of the fields. Some projects, however, were funded to formulate and test new ideas and technologies in a number of areas including coiled tubing, slimhole technology, and other technologies such as high speed drilling and vertical seismic profiling only peripherally related to CT.

DOE Research Since the 1990s

Coiled Tubing

75-97SW41295 and **DE-AF26-98FT02113** (Maurer Engineering Inc., which was acquired by Noble Corporation in 2001 and now does business as Maurer Technology, Inc., a subsidiary of Noble Corporation) Some of the activity in the 1990s was in conjunction with consortiums to leverage research dollars and to assist in technology transfer to as wide as audience as possible. These two consortiums, coordinated by Maurer, were "Project to Develop and Evaluate Coiled-Tubing and Slim Hole Technologies" and Project to Study and Provide Technology Transfer in Area of Coiled Tubing Technology". They resulted in generating a number of industry reports, handbooks and computer software in the application of coiled tubing technologies. In addition, a safety manual and two workshops were performed by Westport Technology Center under **75-97SW41286**.

DE-FC-97FT33063 Another Maurer project, "Advanced High-Pressure Coiled Tubing Drilling System", sought to take a giant leap in depth capabilities. It was to develop a coiled tubing jet-assisted drilling system capable of operating at 10,000 to 15,000 feet. The record at that time was around 5,000 feet and is currently 7,500 feet (True Vertical Depth). At that time, the tubing was not capable of withstanding that pressure without deformation. A somewhat successful test was done with jointed casing. A related project **DE-AC21-94MC31198** was an attempt by Flowdrill to develop and test a slim-hole high pressure pump and also met with limited success in an attempt to take a giant step.

DE-FC26-02NT41662 A more recent project, performed by Penn State "Improved Tubulars for Better Economics in Deep Gas Well Drilling Using Microwave Technology" is testing processes for treating coiled tubing to produce stronger, but still ductile, tubing that if successful could dramatically extend the use of coiled tubing in deeper, longer applications. It is scheduled for completion in July, 2006.

DE-FC26-02NT41316 Gas Technology Institute (GTI) Demonstrated a coiled tubing application beyond the traditional oil and gas well. A robotic system capable of sealing multiple cast iron pipeline bell and spigot joints from a single pipe entry point was designed, tested, and commercialized. This application for pipelines, like the underbalanced well work, demonstrates the advantage of CT in working under pressure.

P-81(FEW 4340-41) and FWP-4340-73 Idaho National Laboratory (INL) has worked from 1998 to 2002 to devise a real time signal analysis for coiled tubing inspection, defect detection and classification. This work and data base will extend the life of the coiled tubing. INL has also been working with the consortium headed by the University of Tulsa to share their data for TU's work in predicting and mitigating tubing failure for the various categories of defects identified by INL.

P-220 In 2000, Sandia National Laboratories conducted a project to develop and commercialize the applicability to coiled tubing of the disposable fiber optic telemetry technology developed for conventional drill pipe. This combined fiber telemetry technology with the cable injection system has been patented by CTES.

Los Alamos National Laboratory (LANL)

For the last 10 years LANL has pioneered drilling with coiled tubing, and in particular the miniaturization of tools and equipment, pursuing the concept of the inexpensive microhole.

P-024 FEWA075 "Advanced Sensor Technology for Microborehole and Other Seismic Applications/Microborehole Seismic Instrumentation". This project, in partnership with Phillips Petroleum and Texaco was active from 1993 to 2002 and was instrumental in miniaturizing seismic recorders. This was the beginning of the merging of the technologies of coiled tubing drilling, microhole technology and vertical seismic profiling and other wellbore seismic applications.

ACTI-105 and **98MC34183** "Multi-Phase Fluid Simulator for Underbalanced Drilling" and "Evaluation of Components and Systems for Bottomhole-Powered Underbalanced Drilling". The purpose of this partnership project was to analyze, model, simulate and demonstrate ultraslim and microdrilling systems and components that were compatible with coiled tubing-deployed directional drilling using multi-phase underbalanced fluids.

P-100 FEWAA02 and **FEW A085-01** “Formation Logging Tools for Microholes” and “Formation Logging for Microborehole”. This partnership project, conducted 1999 – 2002 laid the requisite ground work for the rapid development of a commercial microhole logging capability once the feasibility of deep (up to 5,000 feet or more) microhole drilling was established. The capability and limitations to downsizing various tools was researched. The tools included Gamma Ray, Resistivity, Porosity, and Wellbore Deviation instruments in the 1 ¾ to 2 3/8 inch range.

FWP-LONG1 and **FEWA08E-01** “Coiled Tubing Deployed Microdrilling” and “Coiled Tubing Deployed Microdrilling System with Real Time Downhole Monitoring”. This project is an ongoing test and demonstration of the LANL microdrilling rig. The goal is to drill a 1 3/8 to 1 ¾ inch exploration or monitoring well to 5,000 feet at 1/10 the cost of conventional wells. In this project, the maximum depth achieved was 550 feet in unconsolidated lakebed sediments. Later tests went to 700 – 800 feet.

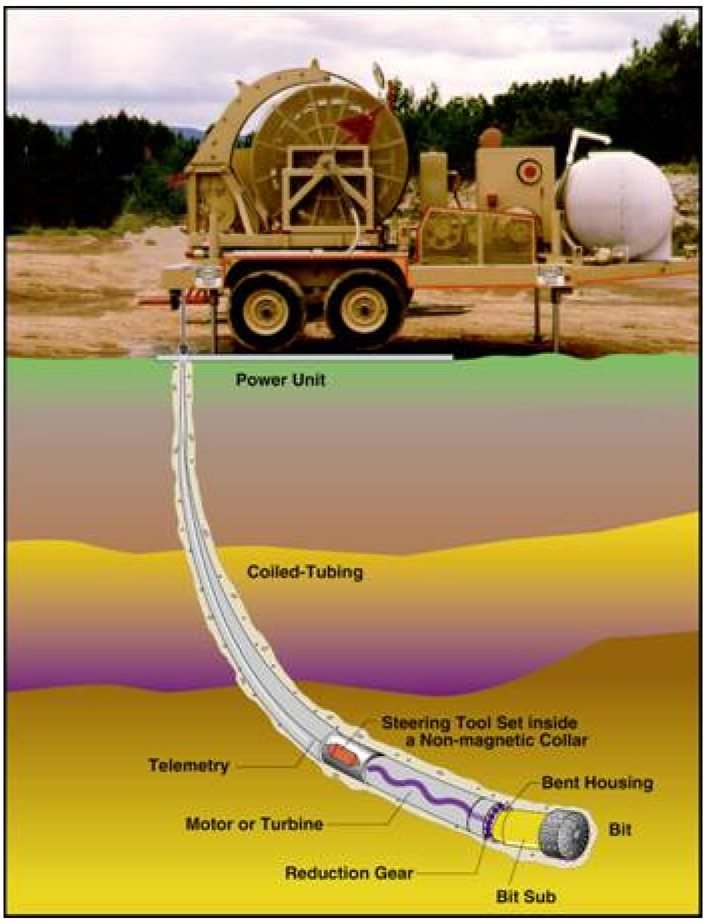

Figure 3. Los Alamos Microhole Coiled Tubing Drilling Rig

CT Related Technologies: High Speed Drilling

As Hart's E&P Net discusses in the August 2004 issue:" ….the concept (ultra high speed drilling) fits with coiled tubing and underbalanced techniques. ….cables can be integrated within the coil…penetration rates will not be held back by production."

DE-AC21-94MC30088 Maurer Engineering "Development and Testing of a High Power, Slim-Hole Drilling System". This 1994 project redesigned a motor (slim hole, multi-lobe) to take advantage of thermally stable diamond bit. They made and tested a 3 3/8 in motor and 3 7/8 – 4 ¾ inch bits. This has been commercialized by Phoenix bit company.

The previously mentioned high pressure jet drilling system tested by Maurer was somewhat successful with jointed pipe, but could not be used with commercial coiled tubing.

FWP-49066 Argonne National Laboratory – IL (ANL) "Application of High Powered Lasers to Drilling and Completing Deep Wells". This 2002 – 2005 project is clearly a big stepout from existing technology. Work includes bench testing lasers burning holes in concrete cores and research and definition of parameters necessary to build a field prototype. If it can be demonstrated to be economical and technically feasible, it could have a large impact in the drilling industry.

DE-AP26-03NT30429 Rio Technical Services "Microdrill Equipment Drawings and Design Specifications". This 2003 project changed early on into an in-depth survey of the current capabilities of hydraulic motors, air/nitrogen motors and electric downhole motors, all in current use for coiled tubing drilling and well service. There are currently available motors and bits in the 2 7/8 inch range that could be conveyed on 1 ½ in coiled tubing in a vertical application. Smaller bits, 1 11/16 inch are used for through-tubing well intervention applications.

CT Related Technologies: Vertical Seismic Profiling (VSP)

The first project by LANL listed in this section explored the concept of miniaturized seismic measuring devices, geophones or micro-electromechanical systems, brought together the coiled tubing microhole drilling technology with seismic monitoring. The proposition is that future IOR and sequestration projects will require a large number of inexpensive wellbores to monitor the progress of the gas saturation. Early DOE sponsored VSP projects include:

P-14 LANL "Binary Explosive Seismic Source Development". This 1991 project evaluated the use of explosives as a source for VSP applications and concluded there were too many impediments.

P-024 FEW A075 LANL "Advanced Sensor Technology for Microborehole and Other Seismic Applications/Microborehole Seismic Instrumentation". This project was active from 1993 to 2003 and evolved from research and design of microelectromechanical System sensors, to building and deploying them in an array for 300 to 800 ft. deep wells drilled with the LANL microhole CT drilling rig for VSP surveys. They have been successfully tested, but so far, are still not as small and effective as the industry standard geophones.

ACTI-074 Lawrence Livermore National Laboratory (LLNL) "Vertical Seismic Profiling While Drilling". This 1995 Project was an attempt to use drill bit noise as a seismic source for a reverse VSP investigation. This concept continues to be pursued by others (Seismic while Drilling) for precise steering relative to the target reservoir.

DE-FC26-01BC15353 University of Houston "Development and Calibration of New 3-D Vector VSP Imaging Technology; Vinton Salt Dome". This 2001 project, aided by OPEX's salt dome prospect and well, combines standard 3-D seismic and downhole VSP data to demonstrate significant increase in seismic information content and potential for greatly improved reservoir imaging and AVO analysis of rock and fluid properties.

DE-FG26-02NT15451 Golder and Associates, Inc. "Multicomponent Seismic Analysis and Calibration to Improve Recovery from Algal Mounds, Ute Mountain and Ute Reservation, CO". This recently completed project was to acquire and process three component, three dimensional seismic data over two algal mound fields and to also acquire three component VSP information to determine the shear wave velocities for processing the shear wave component of this data.

Current DOE Research Focus

The prior DOE sponsored research focus, summarized in the previous section, was geared to making refinements and step outs of existing technology in a number of areas then making them available to DOE's biggest stakeholder, the independent producer. Occasionally, a breakthrough project, such as the laser research was co-funded. While the current thrust of solicitations seeks to improve technology on several fronts to support DOE strategies and goals, much of it is to coordinate several previous loosely related technologies: coiled tubing activities, slim/microhole drilling, high speed motors and bits, and vertical seismic profiling. These technologies are coming together to support the concept of an infrastructure capable of drilling a large number of relatively small bore holes, quickly and inexpensively for the purpose of exploiting shallow gas production, logging and testing exploration projects, and monitoring CO_2 floods, initially for IOR floods, and then for CO_2 sequestration.

CT/Microhole Technology I

Current technology: CT rigs, motors, bits, tubing, bottom hole assemblies for a variety of well intervention and measurement purposes, can drill and complete a vertical hole as small as 4 3/4 inches with 3 1/2 inch pipe set. Horizontal extensions through 3 ½ inch tubing are being drilled in Alaska with a 2 7/8 inch bit conveyed on 2 3/8 inch coiled tubing. Coiled tubing is available in sizes from 1 inch to 4 ½ inches. Motors and bits, primarily for through-tubing well intervention are available as small as 1 11/16 inch. The size, ability to work underbalanced, and precise steering make the smaller tubing and bits the equipment of choice for horizontal extensions of existing vertical wellbores. However, the use of coiled tubing drilling for vertical holes has, for the most part, only been done in Alberta, Canada for a number of reasons explained previously. This equipment was designed to drill 3,000 to 5,000 feet with a 6 ½ inch bit, and set 4 ½ inch casing. When drilled in quantity, these rigs not only compete, but beat the economics of rotary rigs. The recent explosion in drilling CBM wells in Alberta has doubled the CTD wells to over 2,500 annually. The savings is sufficient to make CTD the choice in that hole size, in that geological setting, but does not approach the goal of a smaller hole drilled at the price of working over an older existing well bore for reservoir monitoring and other purposes. The Microhole I Solicitation sought to create the infrastructure – rigs, bottom hole assemblies, mud systems and other hardware, scaled down to drill smaller holes to achieve greater savings, shifting the supply/demand curve for slim/microholes.

DE-FC2604NT15472 Gas Production Specialists, LLC "Development of a Through Tubing Artificial Lift System" will design and develop a submersible pump small enough to provide lift in tubing or microhole.

DE-FC2604NT15473 Baker Hughes INTEQ "Microhole Smart Steering and Logging While Drilling System" will create a 2 inch steering Bottom Hole Assembly (BHA) and motor.

DE-FC2604NT15474 Schlumberger IPC "A Built for Purpose Coiled Tubing Rig". This rig will be modeled after the newer rigs being used in Alberta, but scaled for smaller holes, with less weight, fewer operators, faster rig up time, and easier transport.

DE-FC2604NT15475 Western Well Tool, Inc. "Microhole Downhole Drilling Tractor". The project goal is to design and build a reliable, economical hydraulically powered coiled tubing drilling tractor that will transport the drill bit and tools into long (>3,000 ft.) horizontal holes.

DE-FC2604NT15476 Bandera Petroleum Exploration, LLC "Advanced Mud System for Microhole Coiled Tubing Drilling". This project will develop a mud system for all small diameter CT drilling programs that will circulate the prescribed mixture in a closed (zero discharge) system, eliminating the cost and environmental damage of mud pits.

DE-FC2604NT15477 Stolar Research Corporation "Development of Radar Navigation and Radio Data Transmission for Microhole Coiled Tubing Bottom Hole Assemblies". This project will develop tools for measurement and logging while drilling (MWD and LWD) for microhole BHAs.

Vertical Seismic Profiling (VSP)

Only a handful of CO_2 projects have employed this technology to monitor the movement of the injected CO_2. This process of reservoir monitoring is relatively expensive, but is the technique with the highest resolution and most definitive reservoir view. As more CO_2 IOR projects are embarked upon and CO_2 sequestration proceeds, the need for less expensive monitoring wells will increase. The current DOE sponsored projects are geared to improving the technology and economics of the surveys.

FEW03FE06 LANL "Technology Development and Demonstration of Microhole Oil Production at the Rocky Mountain Oil Test Center". This is a continuation of the demonstration of LANL's CT/microhole rig and it's capability to drill shallow (800 feet) instrumentation wells for the installation of the Micro VSP array. Two (of a planned four maximum) wells have been drilled.

DE-FC26-03NT15426 Temblor Petroleum Co., LLC "Use of Cutting Edge Horizontal, Underbalanced Drilling Technologies, Subsurface Seismic Techniques to Explore, Drill, and Produce Reservoir Oil and Gas from the Fractured Monterey Formation Below 10,000 feet in the Santa Maria Basin of California". This project will use seismic while drilling to guide the exploratory well and VSP to define the reservoir geometry for additional drilling.

DE-FC26-03NT14518 Paulsson Geophysics Services, Inc. "An Integrated Multi-Component Processing and Interpretation Framework for 3D Borehole Seismic Data". This project will result in a one stop software program for the processing and interpretation of three dimensional, three component (3D, 3C) VSP data. Paulsson is a leader in multi-component VSP data acquisition and processing and will be using previously acquired field data.

DE-FC26-04NT15508 Michigan Technological University "Crosswell Seismic Amplitude-Versus-Offsite for Detailed Imaging of Facies and Fluid Distribution Within Carbonate Oil Reservoirs". The project objective is to develop, test and demonstrate a methodology to image the internal architecture and fluid distribution of oil reservoirs at an extremely fine scale using crosswell seismic techniques. If possible, it will be tested on a reef undergoing CO_2 flooding.

DE-FC26-04NT15507 University of Texas at Austin "Combining Borehole Seismic and Electromagnetic Inversion for High-Resolution Petrophysical Assessment of Hydrocarbon Reservoirs". This project proposes to develop algorithms and software infrastructure to jointly invert borehole seismic and electromagnetic data into 3D spatial distributions of petrophysical properties. If successful, this technique could be used to monitor fluid movement over time and help efficiently produce bypassed oil in highly heterogeneous reservoirs.

DE-FC26-03NT15425 Schlumberger Technology Corporation "Application of Time-Lapse Seismic Monitoring for the Control and Optimization of CO_2 Enhanced Oil

Recovery". Based on the results of their forward seismic models, either a surface or subsurface series of seismic images will be generated to monitor a CO_2 flood in a Michigan reef reservoir.

High Speed Drilling

Smaller well bores are driving the need for smaller bits and motors. In order to achieve a high rate of penetration with the reduced weight on the bit, the motor speeds must be faster than the positive displacement or air driven motors in use today for coiled tubing drilling while maintaining a long service life.

DE-FC26-03NT15401 Terra Tek, Inc. "Smaller Footprint Drilling System for Deep and Hard Rock Environment; Feasibility of Ultra-High Speed Diamond Drilling". This project is an offshoot of NASA's Mars program. With an electric motor similar to a dentist's drill, Terra Tek is evaluating the cutting effectiveness of small diamond and diamond impregnated full hole and coring bits, ½ to1 inches in diameter. To date, bench scale tests are being run on sandstone. The high speeds, up to 50,000 rpm, do not appear to be effective on carbonates.

DE-FC26-04NT15501 APS Technology "Novel High-Speed Drilling Motor for Oil Exploration & Production". The project objective is to design and develop a high speed mud motor assembly, comprised of a conventional mud motor and an efficient gearing system to increase the bit speed from 1,000 to 10,000 rpm. The final design should be applicable to horizontal, vertical and multi-lateral wells.

DE-FC26-04NT15502 Impact Technologies, LLC "Advanced Ultra High Speed Motor for Drilling". The project objective is to design and test the feasibility of an ultra high speed electric drilling motor, capable of speeds up to 10,000 rpm. The final product will be a fully modeled and engineered, small diameter inverted motor, sufficient for prototyping the design.

Microhole Technology II (MHTII)

The six projects in the MHT I solicitation generally focused on modeling, design and building a prototype of infrastructure required to support microhole drilling and completion. In comparison, MHT II seeks to move the technology out of the lab and into the field. Below is a summary of projects recently awarded:

DE-FC26-05NT15481 Geoprober Drilling, Inc. "Demonstration of the Use of Composite Coil Tubing to Drill Low Cost (Simple) Deepwater Wells". This is a test of an innovative combination of new and off the shelf technology, the purpose of which is to drill a slim (by offshore standards) exploration well in deep water, but in relatively shallow sediments below the mud line. It is expected that the well can gather wireline log and seismic information and test for hydrocarbons. It would not be capable of production, but would reduce exploration drilling costs by 59%.

DE-FC26-05NT15482 GTI, Coiled Tubing Solutions, Inc. "Field Demonstration of Existing Microhole Coiled Tubing Rig (MCTR) Technology". GTI/CTS will drill at least 3 wells of 1,000, 2,000 and up to 5,000 ft with a built for purpose coiled tubing drilling rig modeled after those in service in Alberta. The holes will be drilled with a 4 ½ inch bit and will set 2 7/8 inch production casing. Costs will be documented and are expected to be less expensive than rotary drilling costs.

DE-FC26-05NT15483 Confluent Filtration Systems, LLC "Advanced Monobore Concept CFEX Self-Expanding Tubular Technology". The project goal is to design and test, in the laboratory and field, a section of an innovative elastic phase, self-expanding tubular.

DE-FC26-05NT15484 Tempress Technologies, Inc. "Small Mechanically Assisted High Pressure Jet Drilling Tool". The project objective is to test the addition of pressurized gas to the drilling fluid, accomplished with a downhole intensifier to operate mechanically assisted, gas shrouded high pressure fluid jets. It is expected to improve drilling efficiency with small positive displacement motors and cuttings removal.

DE-FC26-05NT15485 CTES, LP "Friction Reduction for Microhole CT Drilling". This project, if successful will extend the reach of CT drilling operations without the use of downhole tractors. This will be accomplished through the design and testing of a device to optimally vibrate the tubing on a continuous basis and is expected to dramatically reducing the friction of moving the whole length of coil from a stationary position.

DE-FC26-05NT15486 Technology International, Inc. "High Power Turbodrill and Drill Bit for Drilling With Coiled Tubing". The project objective is to use aerospace technology to design turbine blades and to test a high speed turbine motor and bit designed for high rate of penetration in hard rock.

DE-FC26-05NT15487 Ultima Labs, Inc "Integrated MWD/LWD Measurement System". This goal of this project is to combine Measurement While Drilling and Logging While Drilling Technologies into an integrated low cost system for CT drilling. The device will communicate with the surface through a mud pulse telemetry system.

DE-FC26-05NT15488 Baker Hughes INTEQ "Microhole Wireless Steering While Drilling". This project will build on existing BH 2 3/8 inch steering tools by creating a down-hole bidirectional communication and power module and a surface coiled tubing communication link, eliminating the need for an expensive cable inside the coil.

DE-FC26-05NT15489 GTI, Dennis Tool Company "Counter-Rotating Tandem Motor Drilling System". The proposed drill bit is an evolutionary advancement over existing technology, combining counter-rotating cutter and reamer heads for stability and speed and high-durability PDC cutters to achieve significantly better wear resistance and drilling speed over conventional bits.

DE-FC26-05NT15491 Confluent Filtration Systems, LLC "Microhole Completion and Production Equipment – Self-Expanding – Idealflo Sandscreen Technology". This project is designed to prove and develop a concept for a self-expanding, high-flow sand screen that would be constructed from a range of materials. The prototype will be field tested.

Applications: Industry Acceptance, Market Penetration

Coiled Tubing – Well Intervention

Industry Acceptance

In a 2003 Survey, Spears and Associates report (Reference 16) states global revenues of the Coiled Tubing Services industry were $1 billion, a noticeable number, but still a small part of the overall well drilling and service business. This compares to 2004 total energy services revenues for just three of the many service companies, Schlumberger, B J Services, and Halliburton (excluding their Kellog-Brown and Root Construction subsidiary) of $11.5, $2.6, and $7.0 billion. Nonetheless, coiled tubing services have achieved a high level of acceptance and are growing faster than the services sector in general.

Market Penetration

Coiled Tubing well intervention has a high level of penetration in the market that was restricted to jetting out wells thirty years ago, with rotary workover rigs doing most of the rest. Today, within the limitations of depth, pressure and temperature discussed in the earlier section, CT competes well against the rotary rigs. In a number of applications has an inherent advantage: more precise placement, faster trips, higher ROP in drilling, no joints, allowing underbalanced work. Technology advances have greatly extended the reach and capability of the CT service rig: from stronger tubing, to smarter BHAs, to tractors and connectors to replace weld joints . All of these elements combine to extend the capabilities of the CT rigs at the expense of the rotary workover rigs. In looking at the total market, the US has 1261 working rotary workover rigs (Baker Oil Rig Count, 2005) and 257 CT service rigs (ICoTA rig count). The numbers for Canada are 820 rotary, 269 conventional CT rigs, half of which are shallow service only.

Coiled Tubing – Drilling

Industry Acceptance

Drilling with Coiled Tubing (CTD) has achieved limited acceptance in several specific niches where it has a cost or technology advantage over the rotary rigs. As described in the previous section, there are a number of reasons for this limited acceptance: (1) the tubing strength limits the depth (7900 feet TVD is the record), (2) since it does not rotate, heterogeneous and unpredictable strata can cause it to stick – and fishing is very difficult, and (3) for a one and off well with a general service CT rig (as opposed to a built for purpose drilling rig), the rotary rigs, particularly the truck mounted air rigs, enjoy a cost advantage.

Market Penetration

As indicated above, CTD has penetrated only a few niche markets. In February, 2005 there were 2,745 active (rotary) drilling rigs world-wide. By comparison, there are 42 CT drilling units in Canada (ICoTA 2005 Rig Report), and 1 in the lower 48. There are 9 CT rigs in Alaska that do both service work and drilling the laterals from the existing high angle wells in Prudhoe Bay. Some drilling is done in other international locations with CT service rigs. One area where the CT Drilling has a high penetration rate, limited only by the available rigs, is in the shallow gas well drilling in Alberta. The significant reasons are (1) easy, predictable sediments, (2) specialized equipment, made for exactly that purpose, (3) the ability to schedule dozens of wells at a time, and (4) experienced personnel. In Alaska, CT drilling is used to offset the natural decline of the North Slope. Because the economic returns are quite good, the drilling season is short, and the need for precise steering, the CT units are the drilling equipment of choice. Typically they drill 3 inch laterals several hundred feet out of existing deviated wells. (See References 5 and 23) Currently there is only one CT drilling rig working in the U.S drilling in the shallow gas play in Western Kansas (under DOE contract – Microhole II). In addition there is a specialized completion rig working continuously in the in the CBM play of the Raton basin of New Mexico. Other CT drilling worldwide takes advantage of the ability to drill through existing tubing and drill horizontally underbalanced.

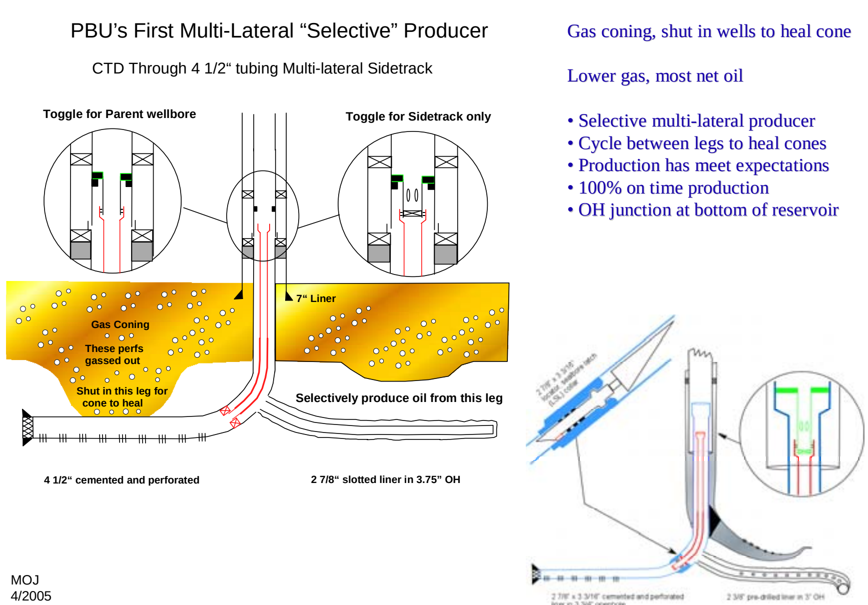

Figure 4. Slimhole Lateral Completions in Prudhoe Bay – Courtesy BP Alaska

Slimhole/Microhole Technology

One of the strategic thrusts of the Oil and Gas Exploration and Production program is to develop the technology for coiled tubing drilling of increasingly smaller (3 ½ inches and under) and less expensive holes. Smaller holes can be drilled with smaller, cheaper and faster equipment, tubulars are less expensive and the process is less intrusive to the environment. The obstacles to overcome include cuttings removal, the increasing chance of getting stuck, depth limitation based on coil strength, limited fluid capacity (for production and fracing), and the need to develop smaller tools and BHAs. There are a number of potential applications for such shallow inexpensive wells: low production volume dry gas wells, logging and seismic for exploration (a non-producing wildcat), small laterals out of vertical wellbores – essentially long, clean, precisely placed, perforations, and monitoring of gas injection, particularly CO_2 for IOR and eventually sequestration.

Shallow Production

Industry Acceptance

Ninety percent of the shallow producing wells drilled with coiled tubing are drilled in the shallow conventional and CBM gas plays in Alberta. They are all drilled with 2 7/8 inch tubing and a 6 ½ inch bit. They are completed with 4 ½ inch casing. There are commercial tools and technologies available today to reduce the casing to 2 7/8 inches, but the producers have chosen not to. In a recent survey taken by Schlumberger of 40 – 50 producers, there was little or no acceptance of the concept. In the Alberta model, the wells are drilled in 12 hours "spud to spud", so the total rig cost is $10,000 to $15,000/well leaving little room for improvement using smaller tubing and bits. The primary savings would be in the tubulars, which could amount to $10,000 - $20,000 depending on which sizes you compare and the depth. The producer must weigh that potential savings against the need to have specialized tools to get into the hole for well completion and intervention, potential of losing the hole, and difficulty of lifting any fluids out of the hole. Thus far they have all come down on the side of paying more for larger diameters.

Market Penetration

The ultimate potential market, however is quite large. Of the 25,705 completions in the lower 48 in 2003 (EIA 2003 Annual Energy Review) 7,800 (RigData) were gas wells shallower than 5,000 ft. Even if one assumes half of those wells produce water and are not candidates for slim/microhole, that still leaves a potential of 3,900 completions at a depth of less than 5,000 feet annually. By comparison, ICoTA has estimated that the number drilled there with coiled tubing exceeds 3,000/year with the recent upsurge of CBM wells.

Exploration Logging and Seismic Survey

Industry Acceptance

The drilling of smaller exploration wells to be used only to log, survey and test, but not produce from the target formation has been discussed in the literature. As described in the Microhole II section previous, a research project has been selected for co-funding to drill an offshore exploration well in deep water, but relatively shallow target formation below the mud line. Since the last string is slim, the starting conductor and subsequent strings are smaller and less expensive as is the drilling equipment. The Principal Investigator estimates savings of 59%. The same principle should prevail onshore. A final liner of 2 7/8 inches, would allow for logging and seismic surveys and well test sufficient to define the reservoir at half the cost of a final casing of 4 ½ or 5 ½ inches.

Market Penetration

Given the fact that 60 % of the 2600 exploration wells drilled in 2003 (EIA 2003 Annual Energy Review) were dry and abandoned, a 50 % savings on all wells and sacrificing the potential to produce from 40% makes economic sense - more so, if you assume a fair number of those not deemed dry are never produced, or optimally located, as the PI referenced above suggests.

Lateral Extensions

Industry Acceptance

Lateral extensions and multi-lateral extensions have been available to producers for several years. The long-term program in Prudhoe Bay was discussed above. For shorter, smaller diameter extensions, there are small turbine motors that are 1 11/16 inches in diameter. Deeper, higher pressure, higher temperature applications become problematical, but the service companies continue to make evolutionary changes to improve bits, motors and bottomhole assemblies to expand this application. Much of the remedial work is performed through production tubing.

Market Penetration

Multi-laterals in new wells are becoming more efficient producers as the downhole measuring and steering becomes more precise. No estimate has been made for the potential of this growing market, but it is considerable and global.

CO_2 IOR and Sequestration Monitoring

A potential driver for the demand for lower cost slim/micro holes is for the monitoring of CO_2 flooding, for enhanced oil recovery in the near term and for sequestration in the long term. The wells could be used to collect seismic data in a VSP or cross well seismic survey as well as passive “smart” wells monitoring pressure, temperature, near wellbore saturations and other changes in the reservoir.

Industry Acceptance

To date, the use of monitoring wells for full scale CO_2 IOR floods has been nearly non-existent. There have been several barriers to the use of VSP on a full field basis. The greatest is cost. The price of a single survey at 5,000 feet is $400,000 for an image of a single cylinder 3,500 feet in diameter and 5,000 feet deep. To monitor the movement of the CO_2 and oil bank, at least three and as many as five surveys are required before injection begins and several times after. Related to the cost of the surveys is the fact that CO_2 floods themselves are very expensive, both in terms of capital outlay for wells, injection facilities and processing plants as well as the cost of the CO_2. Where it has been used beyond the pilot well stage, at Weyburn and West Vacuum fields, it was combined with surface seismic and yielded incomplete results. For the limited number of surveys, existing wells were used to temporarily deploy the arrays. The value of VSP to the producers today appears to be in the pilot phase to monitor injection patterns and behavior to build models for predicting the full field performance. The full field is monitored through injection and production well tests and measurements.

Potential Market

However, according to the experts in the field, the use of VSP in monitoring the effectiveness of sweep in a CO_2 IOR application can improve the tertiary oil recovery by 20 percent or more. Even at the prices cited above it can be economic on a full field survey. The average field incremental oil recovery in a CO_2 flood in the study described below is 34 million barrels. A twenty percent improvement would yield an additional $175 million in revenues at a net revenue of $25/barrel. Even at $250,000 per survey/well, that would pay for more than 30 surveys (or one survey at 30 monitoring wells) a year for 20 years.

Assuming the push for CO_2 sequestration leads to low or no cost CO_2 delivered to the target field and the demand for monitoring the long term effects of the injection drives the acquisition and processing costs down, the number of monitoring wells could grow substantially. To test the limits of that demand, two cases were generated with the CO_2 Miscible Predictive Model (COPM), a component of the Combined Oil and Gas Analysis Model (COGAM). The first case examined the capacity of only those oil fields that have been, or are being water flooded and are sufficiently deep to achieve miscibility to determine the maximum amount of CO_2 that could be retained, the amount of oil that is produced in the process, and the number of wells needed to accomplish the flood. The model only looks at the capacity without regard to economics in general or the price of the CO_2, so essentially it is free. The second case was run under the same assumptions, except all reservoirs were considered, whether previously water flooded or not. The first case would approximate ultimate IOR under today’s economic environment, other than the no-cost CO_2. The second case would more approximate a scenario in which the objective is to maximize the amount of CO_2 sequestered, regardless of the cost of the operation. The results of the analysis are summarized below.

	Case I	Case II
Total Number of Fields	290 (1)	780
Number of Patterns	76,419 (2)	164,604
Total Oil Recovered, Million Barrels	9,763	26,370
CO_2 Sequestered, Million Tons	4,686 (3)	12,658
CO_2 Sequestered/Barrels of Oil Recovered, MCF	8.1	8.1
Average Number of Patterns/Field	264	212
Average EOR recovery/Field, Million Barrels	34	34
Estimated Number of Monitoring Wells	7,250 (4)	19,500

(1) In both cases, only fields with 5 million or more barrels of incremental oil were considered. They account for over 80% of the total potential.
(2) In the model, a pattern is a 5 spot, one injector and one net producer. The model determines the optimal spacing based on reservoir characteristics. By eliminating the fields with less than 5 million barrels, 75 percent of the fields had 50 or more patterns. This is comparable to the 70 – 80 currently producing CO_2 recovery projects.
(3) For reference, anthropogenic CO_2 emission from all stationary sources is 1,935 million tons, giving the two cases 2.4 and 6.5 years capacity for 100% of the U.S. stationary emissions. Other studies sponsored by the DOE that included immiscible sequestration identified 20 years capacity.
(4) As discussed earlier, a full field would be a combination of VSP and surface seismic and passive smart wells. It is assumed for this analysis that there would be one monitoring well for every 10 patterns (20 producers and injectors).

This study suggests that if the U.S. continues down the path to separate, transport and inject CO_2 in geological formations as a solution to the Greenhouse Gas issue, several tens of thousands of monitoring wells will be required in the just the first formations, depleted oil, to sequester the gas. In the very long term, as sequestration targets depleted gas reservoirs, saline reservoirs and unmineable coal many times more wells than shown in this study will be required. Obviously, for this to proceed, it will take action by the Government to compel the emitters to capture and pay for the sequestration through a tax or a system of credits for new sources similar to the NO_X and SO_X credits traded today.

DOE Roadmap: Bridging the Technology Gap

Coiled Tubing – Well Intervention

Much of the progress in expanding applications and reach in well intervention has been accomplished by the larger service companies. Recent examples are the tapered coiled tubing announced by Halliburton and the couplings engineered by B J Services. As they are interested in expanding sales of CT services, their research is developmental in nature. Most of the basic research is being performed by technology companies (generally supported by industry consortiums, sometimes with DOE participation as discussed earlier. In addition, basic research in the strength of materials is being conducted by Penn State, the University of Tulsa and the Idaho National Laboratory. This combination of industry and government support of basic research, particularly in stronger, cheaper coil, with the large service companies focused on new products has made continuous progress in commercializing new products to expand the applications of coiled tubing. Industry acceptance for new applications is growing but still tends to cluster at the small end for well cleanup, and the high end underbalanced, deep (expensive) jobs. The exception is the fast growing use of CT for stimulation, particularly in CBM applications utilizing its ability to precisely stimulate multiple seams and a market that allows for continuous operation.

Coiled Tubing Drilling

Vertical drilling from surface with coiled tubing has not been a priority with either the independent producers or the service companies as discussed earlier. Operators do not believe it can compete economically and service companies do not see it as a high margin (or demand) business to justify the rig fleets and expertise found in Alberta. There have been a number of attempts to spread the use outside of Alberta to the lower 48 and elsewhere in the world, but they never advanced past the pilot stage. Published economics for the same services as would be provided by rotary equipment were usually characterized as equal or cheaper with the CT, once the crews got up the learning curve, but never so compelling as to catch the attention of industry.

On the other hand, high angle drilling from existing vertical or deviated wellbores is growing worldwide. Applied research by the service companies and motor and bit companies continually extends the reach of this technology, now greater than 3,000 feet.

Very little research is being conducted on CT vertical drilling from surface beyond that which is sponsored by the DOE, with particular emphasis on the very small holes and rig such as used by LANL. Until there are demonstrated benefits of slimhole CT drilling and industry acceptance, it will be very difficult for the CT conveyed microhole market to develop.

Slimhole/Microhole Technology

Based on the demonstrated success, technical and economic, of slimhole drilling, smaller tools that can be used through production tubing have been engineered, produced and put in the field by the service companies, motor manufacturers and bit companies. Because of the small sizes and tight clearances, these tools are generally CT conveyed. There are a number of commercial motors, bits and other downhole assemblies in the 2 3/8 to 3 inch size. A few specialized well intervention bits are available that are 1 11/16 inch. The value of all of these, however, is viewed by industry for well intervention and drilling laterals from existing wellbores. Outside of the DOE sponsored research, there is no activity to drill vertical microholes from the surface.

Industry's approach to smaller equipment has been evolutionary, such that there is the technology available today to set 3 ½ or even 2 7/8 inch casing, if not the demand. DOE's approach has been revolutionary, driving directly to creating a completely new infrastructure capable of even smaller holes in an effort to achieve greater savings with the smaller, built for purpose equipment. Clearly, there is a point at which smaller is not cheaper and it has not been determined where that point is, or if evolution is the better approach. It will be very difficult for a market to develop for the very small holes before the demand and acceptance of the low end (3 ½ to 2 /78 inch) slimhole and of the demonstrated economics of coiled tubing vertical drilling.

High Speed Drilling

As discussed earlier, the demand for microhole technology will be driven by the merging of several technologies: small built for purpose CT drilling rigs and equipment, high speed motors and bits, and lower cost VSP for inexpensive monitoring wells.

As it relates to high speed motors and bits, the situation is much the same as slimhole/microhole technology discussed above. Industry is conducting applied research to produce commercial products to meet the "next" need. DOE funded research is focused on the quantum leap with lasers, high pressure jets, and motors 10 times faster than today's commercial downhole motors. The laser and high pressure jetting is a long way from being commercial, but perhaps will produce something to build on. Three different motor types are to be built to increase speed ten fold. The questions that must be answered are (1) will there be a bit or bits to take advantage of the speed, (2) can anything that fast be balanced and reliable, (3) will they work on heterogeneous strata, and (4) will they achieve a spud to TD ROP substantially better than today's state of the art, which is already 3 or more times faster than a rotating rock bit?

Vertical Seismic Profiling

VSP is a technology that has been around for decades. The recent ability to acquire high quality, 3-D, 3-C data over time (4-D) to monitor fluid movement in the reservoir makes VSP of interest to many industry insiders. As with surface seismic, the ability to acquire data has outstripped the software to process it for the maximum information. Much of the industry research, funded by consortiums and government, is geared to improve processing, to maximize resolution and ability to characterize fluid as well as rock properties and to apply these technologies to real reservoirs. In addition to the robust projects conducted by Paulsson, BEG in Austin and others, DOE is funding projects on the other end of the economic spectrum through LBNL and LANL with the miniaturization of geophones, placed in shallow wells. The information provided by the shallow VSP will identify formations and faults, but lacks the resolution of the deeper, and much more expensive 3-D, 3-C VSP. Future research activity must create a more standard processing software, merged with the interpretation that can be accomplished by all seismic processing entities, not just the five that can do it at present. With that, the price will go down, demand will then go up. The end point is to make it affordable for today's IOR projects and be the monitoring tool of choice when CO_2 becomes separated and sequestered as part of a National policy.

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